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Influence of the percentage of sand on the behavior of gap-graded cohesionless soils

Ndriamihaja Livah Andrianatrehina [a], Hanène Souli [a,*], Joël Rech [a], Jean-Jacques Fry [b], Jean-Marie Fleureau [c], Saïd Taibi [d]

[a] *Université de Lyon, École nationale d'ingénieurs de Saint-Étienne (ENI Saint-Étienne), Laboratoire de tribologie et dynamique des systèmes, CNRS UMR 5513, 58, rue Jean-Parot, 42023 Saint-Étienne cedex, France*
[b] *Électricité de France, Centre d'ingéniérie hydraulique, 73073 Le Bourget-du-Lac cedex, France*
[c] *Laboratoire de mécanique des sols, structures et matériaux, CNRS UMR 8579, École centrale Paris, Grande voie des Vignes, 92295 Châtenay-Malabry, France*
[d] *Laboratoire "Ondes et milieux complexes", CNRS UMR 6294, Université du Havre, rue Philippe-Lebon, 76600 Le Havre, France*

A R T I C L E I N F O

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A B S T R A C T

In this work, the effect of the fine content on the undrained mechanical behavior of a granular material is studied. Consolidated undrained triaxial tests were carried out on sand and gravel mixtures. The intact sample contains 30% of sand. In order to simulate suffusion in the sample, degradation consisted in reducing the fines amount to 20, 10 and 5%.
The undrained peak strength and the dilative phase amplitude decrease when the fine content decreases, with the highest values for the intact sample and the lowest values for the sample with 5% fines. On the other hand, the contractive phase progressively increases with the fine content. The degraded samples present a higher internal friction angles than the intact one.

1. Introduction

The detachment and transport of the finest elements of a soil under the effect of water flow in a porous medium is called internal erosion or suffusion. The effect of this phenomenon on the mechanical properties on soils is complex and has received little attention until recently.

Several authors analyzed in detail the phenomena occurring in a sample subjected to suffusion. Chang and Zhang [1] carried out downward flow tests on a granular sample and highlighted the existence of several "critical" suffusion hydraulic gradients: (i) the "initiation" gradient (around 1) corresponding to the first movement of fines, (ii) the "skeleton deformation" gradient (around 2), and (iii) the "failure" gradient (around 7). They showed that these critical gradients depended on the stress state. Ke and Takahashi [2] performed upward flow tests from which they also derived several critical gradients, much lower than in the case of downward flow. They showed that, whatever the value of the initial fine content, the final fine content was more or less the same at the end of the suffusion tests. They evidenced the fact that, from a certain hydraulic gradient, suffusion occurred in the shape of "sand volcanos", and not uniformly in the surface of the sample. This

* Corresponding author.
E-mail addresses: milivah@yahoo.fr (N.L. Andrianatrehina), hanene.souli@enise.fr (H. Souli), jean-jacques.fry@edf.fr (J.-J. Fry), jean-marie.fleureau@ecp.fr (J.-M. Fleureau), Said.Taibi@univ-lehavre.fr (S. Taibi).

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observation was confirmed by the measurements of Sail et al. [3], who observed the formation of a blowout, first at the surface, then progressing downward after one hour under a gradient of 5. Apart from the effect of stress, Bendahmane et al. [4] and Marot et al. [5] showed that suffusion also depended on several factors, e.g. the angularity and initial density of the particles. Ouyang and Takahashi [6] related the effect of the fine content to the fabric of the soil subjected to erosion. The conclusion of these tests is that it is difficult to study directly the behavior of a sample subjected to suffusion as this sample will present heterogeneity of the grain size distribution, both vertically and horizontally.

In other studies, the authors tried to study the effect of suffusion on the mechanical properties of a soil, either by subjecting a sample to a suffusion test before the mechanical tests, or by preparing homogeneous samples supposed to represent the material after the suffusion tests. Ke and Takahashi [7] performed CPT tests on samples with the same initial relative densities, different initial fine contents, and more or less the same fine content after the suffusion tests, to assess their strength. They measured a slight increase in cone-tip strength when the initial fine content decreased. Chang et al. [8] showed a slight decrease in peak friction angle during suffusion when the loss of fines increased. Zhao et al. [9] carried out compression, CD and CU triaxial tests, as well as microstructure observations, on binary mixtures of grains with the same initial void ratio. They observed that the sample with a fine content approximately equal to 30% (corresponding to the filling of the pores of the coarse particles by the fines) presented the highest isotropic compressibility, a contracting behavior on triaxial path, and the smallest strength. On the contrary, the sample with a fine content lower than 30% was the less compressible, highly dilative and with the highest strength. The sample with a fine content higher than 30% featured an intermediate behavior. However, in these tests, the void ratio was kept constant and, as the fine content changed, it means that the maximum and minimum void ratios also changed, as well as the relative density of the samples.

Dash et al. [10] show that the mechanical properties of granular soils primarily depend on relative density. The behavior of soils is also depending on the grain size distribution curves of the materials as shown by Liu et al. [11], the angularity and shape of the grains, etc. It is important to mention that the angularity and the shape of the grains play an important role in the suffusion as demonstrated by Kovac [12] and Marot et al. [13].

Some works studied the effect of suffusion on the mechanical behavior of samples by means of numerical models. Scholtès et al. [14], Hicher [15], and Muir Wood et al. [16] simulated the suffusion process by a progressive reduction of the fine content. Scholtès et al. [14] and Hicher et al. [15] used a multiscale model to describe the change in the mechanical properties of a soil subjected to consolidated drained (CD) triaxial tests. They showed that degradation of the granular samples led to a decrease in the strength of the material. The authors related this behavior to the more organized structure of the samples. Moreover, degradation of the samples changed gradually their behavior from dilative to contractive. Muir Wood et al. [16], using DEM analysis, showed that degradation of samples resulted in the rising of the critical state line in the compression plan.

In this article, the interest is focused on the study of the evolution of the mechanical behavior of the samples when the fine content is gradually decreased. The experimental study was carried out on gap-graded granular materials. Consolidated undrained (CU) triaxial tests were performed on samples with different fine percentages and the same initial relative density, under two values of confining stress. This approach does not represent the suffusion phenomenon, which is much more complex, as shown before. However, it is a simplified way to assess how the behavior of the samples evolves when the fine content gradually changes in the process before the fines are totally eliminated. The samples were obtained by mixing a gravel ($2 < d < 16$ mm) and a sand ($0.1 < d < 0.315$ mm). These mixtures were chosen because coarse soils are not frequently studied in the literature and because they correspond to materials that can be found in some dikes or dams. In this work, degradation was simulated by reducing the amount of fines from 30% in the intact material to 20, 10 and 5% in the degraded ones. The effect of degradation was studied by following the evolution of the stress deviator and pore-water pressure during CU triaxial tests.

2. Material and experimental methods

2.1. Samples preparation

The test materials were made from an alluvial deposit coming from the Rhône River in France. The grain size distribution curves (Fig. 1) show that there is no fraction smaller than 100 μm. The grains are in their majority sub-angular. The materials were obtained by mixing two granular fractions, a coarse fraction made of gravel ($2 < d < 16$ mm) and a fine fraction made of sand ($0.1 < d < 0.315$ mm). For these materials, the transition fine content (TFC), i.e. the percentage of fines corresponding to the filling of the voids of the gravel by the sand (Skempton and Brogan [17]), is given by the following expression (Andrianatrehina et al. [18]):

$$TFC = \frac{e_c}{1 = e_c + e_f} = 30\% \tag{1}$$

where e_c is the intergranular void ratio, i.e. the void ratio of the coarse grains, independently of the fines contained in the voids, and e_f is the interfine void ratio, the void ratio of the fines independently of the coarse grains. This formula, is similar to that proposed by several authors (Dash et al. [10]; Emdadul Karim and Jahangir Alam [19]; and Chang et al. [5]) to characterize the fine content corresponding to the change from "sand-dominated" behavior to "gravel-dominated" behavior.

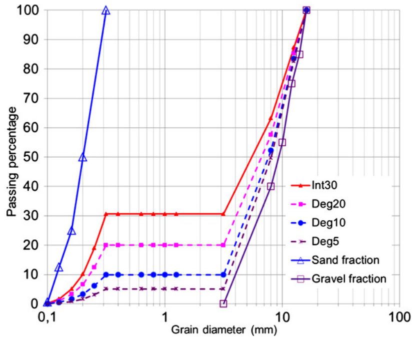

Fig. 1. Grain size distributions of the gravel fraction, sand fraction and studied materials (Int30, Deg20, Deg10 and Deg5).

Table 1
Uniformity coefficients of the prepared samples.

Name	Sand content (%)	Uniformity coefficient C_u	Minimum void ratio e_{min}	Maximum void ratio e_{max}	Initial void ratio corresponding to $D_r = 60\%$
Int30	30	37	0.17	0.36	0.24
Deg20	20	35.7	0.19	0.38	0.26
Deg10	10	2.9–29	0.43	0.55	0.47
Deg5	5	2.6	0.44	0.58	0.49

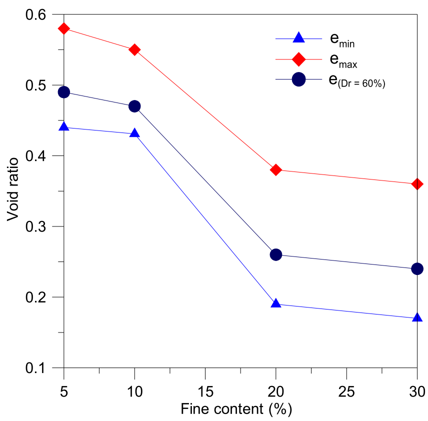

Fig. 2. Standard minimum and maximum, and initial void ratio evolution for the tested materials.

Based on this result, the intact sample Int30 was prepared with a sand fraction equal to the TFC. The grading curve of this sample is shown in Fig. 1. This sample presents a uniformity coefficient (C_u) higher than 5, which indicates that the grain size distribution is widely graded (Table 1). According to measurements and the Kenney and Lau [20,21], Kézdi [22], and Burenkova [23] internal stability criteria, the sample Int30 is classified as unstable.

In the case of this study, the degradation of the samples consisted in progressively extracting the fine fraction from the voids. The amount of fines was reduced to 20, 10 and 5%. These samples are called Deg20, Deg10 and Deg5, respectively. The grading curves of these samples are shown in Fig. 1, and their characteristics in Table 1. All the samples are gap-graded.

The sample Deg20 presents a uniformity coefficient (C_u) higher than 5, which indicates that the grain size distribution is widely-graded. For the sample Deg5, the uniformity coefficient (C_u) is smaller than 5, which means that the material is narrowly-graded. For Deg10, the uniformity coefficient cannot be easily determined, because d_{10} (the diameter for 10% passing grains) corresponds to the plateau of the grading curve.

Table 1 and Fig. 2 present the evolution of the maximum (e_{max}) and minimum (e_{min}) void ratios of the studied samples, determined using the ASTM standards [24,25]. Table 1 and Fig. 2 also show the values of the initial void ratios corresponding to the constant preparation relative density of 60%.

The sample Int30 presents the lowest e_{min} and e_{max} values, whereas the samples Deg20, Deg10, Deg5 show a progressive increase in e_{min} and e_{max} when the fine content decreases. These changes are related to the changes in the uniformity coefficient, from 37 for Int30 to 2.6 for Deg5. Youde [26], Poulos [27], Biarez and Hicher [28], Cubrinovski and Ishihara [29], Simioni and Houlsby [30] indicated that the decrease in e_{min} and e_{max} when the uniformity coefficient increases was due to the ability of well-graded samples to form denser packing, and this trend is also observed in most correlations of e_{min} and e_{max} with the uniformity coefficient C_u.

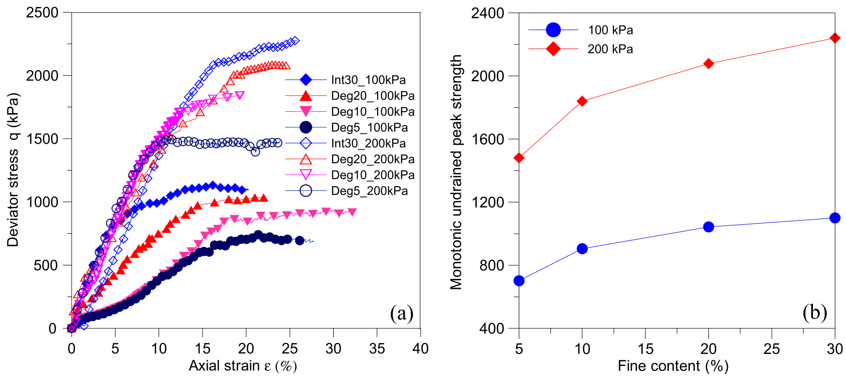

Fig. 3. (a) Undrained triaxial test results in the $[\varepsilon, q]$ plan under confining stresses of 100 and 200 kPa. (b) Evolution of the monotonic undrained peak strength as a function of the fine content.

Many authors showed that the evolution of the void ratio was strongly sensitive to the fine content. As suggested by Polito and Martin [31], Cubrinovski and Ishihara [29], and Dash et al. [10], for fine contents smaller than the TFC, the fine grains fill the voids between the coarse grains. For a constant volume of the coarse grains, the increase in the void ratio is due to the increase in the volume of the voids between these grains. Therefore, the reduction of the fine content increases the volume of the voids and the void ratio.

Triaxial tests were performed on the samples Int30, Deg20, Deg10 and Deg5. The pluviation method was used to prepare the samples in a mold placed on the pedestal of the triaxial cell, at an initial relative density of 60%. Pluviation was used, instead of tamping, to avoid the possible migration or segregation of grains during the preparation of the samples. After this step, the upper cap was placed on the specimen and the membrane was closed and sealed around the lower and upper ends using torical seals.

The triaxial tests were performed using the following procedure:

(a) saturating the sample in two steps by: (1) circulating water from the bottom to the top under a very small hydraulic gradient to eliminate the main air bubbles and saturate the circuits; the gradient was chosen low enough (<0.1) to ensure that no suffusion occurred during that step [15]; (2) simultaneously and continuously increasing the confining stress and pore-water pressure from initial values $\sigma_3 = 35$ kPa and $u = 15$ kPa to final values $\sigma_3 = 620$ kPa and $u = 600$ kPa, respectively. The objective of this second step was to dissolve entrapped air according to Henry law; it was performed very slowly in order not to perturb the specimens;
(b) checking the value of Skempton coefficient B $(= \Delta u/\Delta\sigma_3)$ by increasing the confining pressure from 620 to 670 kPa under undrained conditions. In all the tests, B values larger than 0.95 were obtained, confirming the good saturation of the samples;
(c) consolidating the sample under initial effective confining stresses of 100 kPa and 200 kPa. This was done by increasing the confining stress while maintaining the back pressure constant;
(d) shearing the sample under constant strain rate (lower than 1% per hour), constant total confining stress and undrained conditions, up to a large axial strain in order to obtain the failure of the sample. The vertical displacement is measured using an LVDT;
(e) Antifriction platens were used to ensure homogeneity of deformations in the samples and avoid formation of barrels. Indeed, even for high axial strain values, the shape of the samples appeared more or less cylindrical.

All the tests were repeated 2 or 3 times to ensure that the conclusions were not subject to experimental scatter. In order to verify that the migration of grains did not occur during the preparation of the samples, or during the saturation or the consolidation phases, the samples were demoulded after these steps and divided into three parts corresponding to the upper, middle and bottom sections. The grain size distribution curve of each part was measured. The results showed that, during these phases, a maximum difference of 2% in passing percentage was observed between the different curves, confirming that migration of grains was negligible.

3. Results of the consolidated undrained triaxial tests

3.1. Stress–strain behavior

The behavior of the studied samples is shown in Fig. 3a in the axial strain – deviator stress $[\varepsilon, q]$ plan. The curves present the evolution of the deviator stress for tests carried out under confining stresses of 100 and 200 kPa.

The results show that, for all the samples, the deviator stress (q) increases for the low values of the axial strain (ε). For the higher values of the axial strain, stabilization of the deviator stress is observed. The shape of the curves shows that no

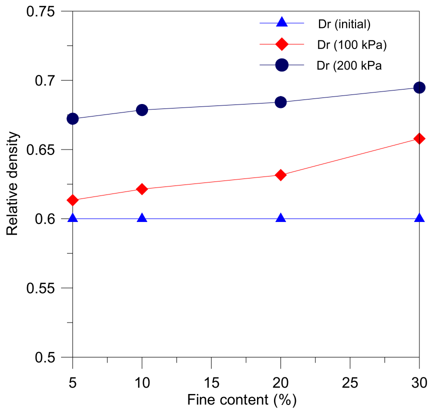

Fig. 4. Evolution of the relative density after the triaxial tests.

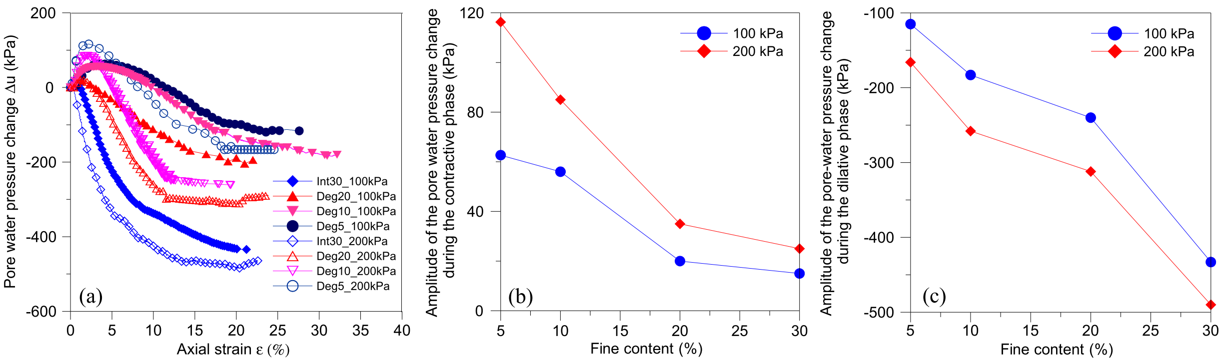

Fig. 5. (a) Undrained triaxial test results in the $[\varepsilon, \Delta u]$ plan for confining stresses of 100 and 200 kPa. (b) Evolution of the contractive phase for the samples Int30, Deg20, Deg10, Deg5. (c) Evolution of the dilative phase for the samples Int30, Deg20, Deg10, Deg5.

liquefaction occurred in theses samples. The tests carried out under a confining stress of 200 kPa present higher deviator stresses than those carried out under a confining stress of 100 kPa.

Fig. 3b presents a comparison of the values of the monotonic undrained peak strength values for the intact sample and the degraded samples. The monotonic undrained peak strength corresponds to the maximum deviator stress values.

Degradation of the samples by reduction of the fine content results in a decrease in the monotonic undrained peak strength. For example, under the confining stress of 100 kPa, the monotonic undrained peak strength is equal to 1040, 905 and 705 kPa for the samples Deg20, Deg10 and Deg5, respectively, compared to 1100 kPa for Int30. The trend is the same for the tests carried out under the confining stress of 200 kPa (Fig. 3b). These results confirm those of Ke and Takahashi [7], who used cone penetration tests (CPT), to show that the strength of eroded materials was smaller than that of intact materials. The results of this paper also confirm those obtained by modeling by Scholtès et al. [14] who predicted a decrease in the strength of the samples when they were degraded.

3.2. Relative densities

In order to understand the deviator stress behavior, the relative densities of the samples Int30, Deg20, Deg10 and Deg5 before and after the CU triaxial tests were plotted in Fig. 4. The void ratios after consolidation, which are equal to the void ratios at the end of the tests, are considered to play an important part in the behavior of the samples.

The sample Int30 features the highest values of the final relative density compared to the degraded samples Deg20, Deg10 and Deg5. Dash and Sitharam [10] suggested that the samples with the highest fine contents presented the highest relative densities, and that these high relative densities were at the origin of the high monotonic undrained peak strength values. This is also what is observed in our tests. As shown in Fig. 3a, the sample Int30 presents the highest values of the monotonic undrained peak strength, followed by the samples Deg20, Deg10 and Deg5.

3.3. Changes in pore-water pressure

In the axial strain–pore water pressure change $[\varepsilon, \Delta u]$ plan, the curves present two phases (Fig. 5a): (i) at low values of the axial strain, a phase of pore pressure increase corresponding, in a CD test, to a contractive phase; (ii) for larger strains, a phase of pore pressure decrease, corresponding to a dilative phase. The results show that the amplitudes of the dilative

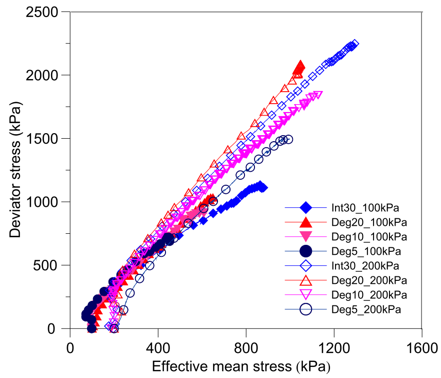

Fig. 6. Undrained triaxial test results in the $[p', q]$ plan under confining stresses of 100 and 200 kPa.

Table 2
Friction angle of the samples before and after degradation.

Name	Sand content (%)	Friction angle (°)
Int30	30	39
Deg20	20	40.5
Deg10	10	41.5
Deg5	5	43

and contractive phases depend on the confining stress and on the degradation of the samples. These observations are more detailed in Figs. 5b and 5c that present the evolution of the amplitude of the contractive and dilative phases as a function of the fine content.

The degradation of the samples greatly influences the amplitude of the dilative and contractive phases. The results in Figs. 5b and 5c show that the intact sample Int30 presents a small contractive phase and a dominant dilative phase under both confining stresses. The degradation of the sample progressively accentuates the amplitude of the contractive phase and attenuates that of the dilative one, with the sample Deg5 presenting the lowest dilative phase and the highest contractive phase. These results are in agreement with those presented by Kokusho et al. [32]. Indeed, degradation of the samples influences the grain size distribution of the curves. The authors explain that the widely graded samples (with high values of the uniformity coefficient C_u) present more pronounced dilatancy phases than the narrowly-graded ones. Dash and Sitharam [10] showed that the increase in undrained monotonic peak strength was related to the increase in the amplitude of the dilative phase. In addition, Scholtès et al. [14] showed by modeling that the intact sample featured a small contractive phase and a large dilative one compared to the degraded ones. The degradation of the samples results in an increase in the amplitude of the contractive phase and a decrease in the amplitude of the dilative one. The results of our study are in agreement with those of Dash and Sitharam [10], and Scholtès et al. [14], the sample Int30 presenting the highest value of the undrained monotonic peak strength (Fig. 3b), the lowest amplitude of the contractive phase, and the highest amplitude of the dilative phase (Figs. 5b and 5c).

3.4. Stress paths

The evolution of the deviator stress q as a function of the effective mean stress p' is shown in Fig. 6 for all the samples and the two confining stresses.

The results shown in the $[p', q]$ plan allow the determination of the failure criterion and of the internal friction angle. The results are presented in Table 2.

The intact sample Int30 presents an internal friction angle equal to 39°. Degradation of the samples results in a progressive increase in the friction angle. This result is consistent with those of Yagiz [33] and Aghaei et al. [34], who showed that the samples with the highest amount of fines featured lower friction angles compared to samples with lower amounts of fines. In fact, change in the friction angle is related to the change in the shape and surface state of the grains. These properties depend on the size of the particles and obviously, on the soil, which explains the diverging conclusions of authors in the literature regarding this parameter.

3.5. Synthesis and discussion

In this research, degradation of the samples due to suffusion was simulated by a progressive reduction of their fine content, from 30% for the intact material (corresponding to the TFC, i.e. the filling of the gravel voids by the sand particles) to 20, 10 and 5%. Degradation results in a decrease in relative density after consolidation, a decrease in monotonic undrained peak strength, an increase in the contractive phase amplitude and a decrease in the dilative phase amplitude. An increase in the internal friction angle is observed in the degraded samples. These results are observed for the tests carried out under both confining stresses of 100 and 200 kPa. The results also show a decrease in the minimum and maximum standardized void ratios and void ratios after consolidation. These results are consistent with those of several researchers, like Ke and Takahashi [7], Scholtès et al. [14]. In these studies the authors explain that extraction of fines results in a progressive reorganization of the samples, leading to another stable state. Skempton and Brogan [17], Chang et al. [8] argue that, in the initial state, i.e. when the fine content is equal to the TFC, the fines also contribute to supporting the stresses. Their extraction causes a weakening of the force chains.

On the other hand, the results presented by Ouyang and Takahashi [6], and Ke and Takahashi [2], show that reduction of the fine content leads to an increase in the soil strength. They explain this result by the increase in the contact points between the coarse grains due to the elimination of fines after erosion. In that case, elimination of fines results in a reorganization of the coarse grains and a significant decrease in void ratio. By contrast, in the present work, compressibility of the coarse fraction is small due to the larger size of the particles, so that little reorganization of the particles occurs under the effect of the confining stress. In the initial state, for the fine content of 30%, the voids are totally filled with fines. When the fine content is reduced, the void ratio increases. The change from dilative to contractive behavior when the fine content is reduced is explained by the increase in the porosity of the samples, and the corresponding decrease in their density.

4. Conclusion

The results presented in this work show that the degradation of the mixture of sand and gravel by the extraction of fines has large consequences on the mechanical behavior of the samples:

- the intact sample presents the lowest values of the standardized $e_{\min}$ and $e_{\max}$ void ratios. The degradation of the samples results in an increase of $e_{\min}$ and $e_{\max}$. Indeed, there are less and less fines to fill the voids between the coarse elements when the soil is degraded. For a constant volume of coarse grains, the reduction of the fine content results in an increase in the volume of voids and therefore, to an increase in void ratio;
- the intact sample Int30 presents the highest value of the monotonic undrained peak strength under both confining stresses The decrease in monotonic undrained peak strength is related to the destabilization of the force chains as the fine content is reduced, resulting in grain rearrangement and the formation of a new balance state, which is not compensated by the consolidation of the soil. In addition, the density of the samples decrease as they are degraded;
- the intact sample Int30 presents a dilative behavior. The amplitude of the contractive phase is very small, as the porosity of the sample is low. The degradation of the samples results in a decrease in their monotonic undrained peak strength. The results highlight a significant increase in the contractive phase and a decrease in the dilative one. These changes are all the more important as the fine content decreases;
- the friction angle of the soil increases when the fine content decreases. This aspect is related to the change in the fabric of the material, allowing more direct contact between coarse grains, but also to the angularity and surface properties of the various fractions of grains.

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